

Supply generator for an oscillatory circuit, particularly
for an induction cooking hob

The present invention relates to a supply generator for an oscillatory circuit.

5 It also relates to a set of such generators and to an induction cooking hob comprising a plurality of generators of the invention.

10 The present invention is aimed generally at induction heating systems, in particular cooking hobs comprising a plurality of induction cooking rings supplied by respective generators.

These induction cooking hobs necessitate the generation in the container or material to be heated of a current at a high frequency, of the order of 20 to 50 kHz.

15 In the conventional way, this current is created by a magnetic field produced by an inductor coupled to a power generator.

That power generator is generally a resonant generator, as shown in figure 1.

20 That power generator is supplied with power from the electrical mains supply at a rectified and filtered supply voltage E.

25 Thus each cooking ring F, comprising an inductor and a resistive load R consisting in particular of the container to be heated, is associated with resonant capacitors C_3 , C_4 to form a circuit resonating at an angular frequency ω such that $L(C_3+C_4)\omega^2 = 1$.

30 The greater the combination of the chopping frequency and the generator power, the higher the resonance.

In induction systems, this is the case in particular when the chopping frequency is at least 20 kHz and the power of the generator is of the order of 3 kW.

35 The use of these resonant generators enables a maximum power to be transmitted to an inductive load at the

resonant frequency of the supply system.

To prevent overheating of the semiconductors, it is possible to operate the semiconductors of these power generators with zero switching losses.

5 Accordingly, in the conventional way, a soft switching mode in which switching occurs at the zero voltage crossing of the transistors I_1 , I_2 is obtained by providing the transistors I_1 , I_2 with diodes D_1 , D_2 and capacitors C_1 , C_2 in the usual way.

10 To preserve these soft switching modes, the generator power is generally adjusted by adjusting the operating frequency around the resonant frequency.

Power modulation by varying the operating frequency of the generator in this way has many drawbacks, however.

15 In particular, the frequency range in which the generator operating frequency must be varied is relatively wide if the modulated power is required to vary in a wide range (for example in a ratio from 1 to 10).

20 Furthermore, if a plurality of resonant generators are operating in parallel, it is impossible to synchronize them if it is required to retain the possibility of independent power modulation.

25 Intermodulation noise is then generated between the generators operating close together at different frequencies.

One example of the above type of soft switching resonant generator is disclosed in the document FR 2 792 157 in particular.

30 That document describes a solution in which a plurality of inductors may be controlled by the same voltage and at the same frequency but with a duty cycle that may be adjusted using the pulse width modulation (PWM) technique well known in the art.

35 However, in the document FR 2 792 157, this mode of operation necessitates the use of particular structures

introducing the concept of a master generator and slave generators whose operation is linked to the operation of the master generator.

5 This type of structure is not very suitable for a set of induction cooking rings in which each of the rings must operate independently, without a master and one or more slaves being defined.

10 An object of the present invention is to eliminate the drawbacks cited above and to propose a supply generator for an oscillatory circuit allowing power modulation with a high power ratio at a fixed frequency.

15 To this end, the present invention is aimed firstly at a supply generator for an oscillatory circuit comprising an inductor and a resonant capacitor adapted to operate at a fixed frequency and comprising at least one pair of transistors controlled at a variable duty cycle to modify the power.

20 According to the invention, the generator comprises a first diode between a first transistor of the pair and the supply of the generator and a second diode between the connection point of the inductor and the resonant capacitor and the connection point of the first transistor and the first diode.

25 Thanks to this particular arrangement, the operating phase of the generator in which the second diode conducts is relatively short.

30 This operating phase, corresponding to linear operation of the generator, is therefore very short in relation to the resonant operation of the generator, with the result that the latter's output power may be maximized.

According to a preferred feature of the invention, the transistors are associated with diodes and capacitors adapted to operate the generator in a soft switching mode.

35 There is obtained in this way a supply generator operating at a fixed frequency, at resonance in order to

obtain maximum power in an inductive load, and in the zero voltage switch (ZVS) soft switching mode in which switching occurs at zero voltage and at the nominal current.

5 This switching mode prevents excessive heating in the semiconductors constituting the power generator.

The present invention is also aimed at a set of supply generators according to the invention said generators being synchronized in frequency and controlled at different duty cycles.

10 Finally, the present invention is further aimed at an induction cooking hob comprising a plurality of inductors adapted to constitute one or more cooking rings of said hob.

15 According to the invention, each inductor is associated with a supply generator in accordance with the invention, said generators being synchronized in frequency and adapted to be controlled independently of each other with a variable duty cycle.

20 Other features and advantages of the invention will become further apparent in the course of the following description.

In the appended drawings, which are given by way of non-limiting example:

25 - figure 1 is an electrical circuit diagram of a prior art supply generator described hereinabove;

- figure 2 is an electrical circuit diagram of a first embodiment of a power generator of the invention;

30 - figures 3, 4 and 5 are curves showing for different duty cycles the values of the voltages and the currents at various points of the figure 2 electrical circuit;

- figure 6 is an electrical circuit diagram of a second embodiment of a supply generator of the invention;

35 - figure 7 is an electrical circuit diagram of a third embodiment of a supply generator of the invention;

and

- figure 8 is a block diagram of a set of supply generators of the invention.

5 An electrical circuit of a first embodiment of a supply generator of the invention is described first with reference to figure 2.

10 That generator includes two transistors I_1 , I_2 in a half-bridge configuration and supplied at a voltage E corresponding to the rectified and filtered voltage of the mains electrical power supply.

15 In the conventional way, these transistors I_1 , I_2 are associated with diodes D_1 , D_2 and capacitors C_1 , C_2 in a configuration allowing switching in the zero voltage switching (ZVS) mode, which is a soft switching mode in which switching occurs at the zero crossing of the voltage.

The oscillatory circuit supplied by the transistors I_1 , I_2 consists of an inductor L and resonant capacitors C_3 , C_4 .

20 This type of resonant generator transmits maximum power to inductive loads of the L , R type such as are found in induction cooking rings, in which the load consists of an inductor and a container to be heated.

25 For example, L may have a value of the order of 50 μH and the resonant capacitors C_3 , C_4 may have a value of 680 nF.

According to the invention, a first diode D_5 is connected in series with one of the transistors of the half-bridge, here, by way of non-limiting example, the transistor I_2 .

30 This first diode D_5 is therefore connected between the transistor I_2 and the supply voltage E of the generator.

A second diode D_4 is connected in parallel with a resonant capacitor C_4 .

35 This second diode D_4 is therefore connected between

the connection between the inductor L and the resonant capacitor C_4 and the connection between the transistor I_2 and the first diode D_5 .

5 The diodes D_4 , D_5 are connected so that the cathode of the second diode D_4 is connected to the cathode of the first diode D_5 .

Of course, an equivalent circuit could be obtained by connecting a diode in series with the other transistor I_1 of the half-bridge and a diode across the other resonant capacitor C_3 .

10 The operation of a generator of the above kind controlled by control means that are not shown is described next with reference to figures 3, 4 and 5.

Those figures show in continuous line the voltage as a function of time at the point A of the figure 2 circuit, i.e. the voltage across the transistors I_1 , I_2 .

The dashed line curve shows the current I_L flowing in the inductive load F and the chain-dotted curve shows the voltage at the point B of the circuit, i.e. across the resonant capacitors C_3 , C_4 .

20 The voltage at the point A is a supply voltage at a fixed frequency, with the result that the period T of repetition of the signals is identical in the three curves of figures 3 to 5.

25 The period T_{on} is the time for which the transistor I_2 connected in series with the first diode D_5 conducts.

The power delivered can therefore be varied by modifying the duty cycle δ corresponding to the ratio of the time T_{on} to the signal repetition period T .

30 This duty cycle δ can vary from 0.5 (see figure 4), at which the power is at a maximum, to a value δ_{max} (see figure 5) at which the power is at a minimum.

This value δ_{max} may typically be from 0.8 to 0.9.

35 Thus the power is modulated by modulating the period T_{on} , i.e. the time for which the transistor I_2

conducts, and keeping the period of the signals T constant.

Five distinct phases, numbered 1 to 5 in the figures, can therefore be distinguished over each period T of operation:

5 Phase 1

The transistor I_1 conducts. The current I_L in the inductive load decreases and the resonant capacitors C_3 , C_4 are discharged in resonant mode.

Phase 2

10 The control circuit then turns off the transistor I_1 . The current I_L then charges the capacitors C_1 , C_2 until the diode D_2 conducts, the voltage across the transistors I_1 , I_2 increasing slowly during switching by the ZVS soft switching circuit.

15 During this phase, the resonant mode formed by the current I_L and the resonant capacitors C_3 , C_4 continues.

Phase 3

 The diode D_2 conducts and then the transistor I_2 also conducts. The resonant capacitors C_3 , C_4 are
20 discharged in resonant mode with the result that the voltage at the point B rises to a value sufficient to cause conduction in the second diode D_4 .

Phase 4

 The diode D_4 conducts, with the result that the
25 current I_L no longer flows in the resonant capacitors C_3 , C_4 . The current I_L is discharged slowly into the short circuit consisting of the second diode D_4 and the transistor I_2 , which continues to conduct.

 This discharge occurs exponentially and not in
30 resonant mode, and the value of the voltage at the point B remains equal to the value of the supply voltage E.

 Note that, during this phase 4, the current I_L decreases more slowly than in the resonant mode, the current I_L decreasing with a slope proportional to L/R .

35 Accordingly, at the end of this phase 4, the value

of the current I_L remains positive, with the result that it is possible to turn off the transistor I_2 using a soft switching mode.

Phase 5

5 The transistor I_2 is turned off and, in an analogous manner to phase 2, there is a slow decrease in the voltage across the transistors I_1 , I_2 in the ZVS switching mode.

10 The first diode D_5 is turned off and then the second diode D_4 is also turned off, with the result that the voltage B across the resonant capacitors C_3 , C_4 increases to a value greater than the value of the supply voltage E .

15 This phase 5 then leads to a new phase 1 of a new period T .

 The above operation is exactly the same regardless of the ratio δ selected.

20 In particular, in figure 4, at maximum power, when δ is equal to 0.5, the current I_L flowing in the load is very high, with the result that the power output is at a maximum. In particular, the power delivered by the generator may be very close to that obtained at the resonant frequency with a conventional circuit as shown in figure 1. The power reduction caused by the quasiresonant operation of the generator is of the order of only 25% to 30%.

 Furthermore, the phase 4 during which the second diode D_4 conducts is very short.

30 On the other hand, in figure 5, when the value of the ratio δ is at a maximum, a relatively low current I_L is obtained, corresponding to a minimum power delivered by the generator.

35 It is nevertheless seen that, even in this mode of operation, the current I_L remains sufficiently high at the beginning of phases 2 and 5 to preserve the ZVS soft

switching mode and in particular remains sufficiently high to discharge the capacitors C_1 , C_2 during the switching phases.

Accordingly, this electrical circuit operates at full power in a quasiresonant mode adapted to the inductive loads L , R .

It is possible to operate the generator at a fixed frequency by modulating the power by modifying the bandwidth.

The modulation depth, from $\delta = 0.5$ to $\delta = \delta_{\max}$, is relatively high and corresponds to a power ratio of 1 to 7.

Furthermore, whatever the duty cycle δ selected, the soft switching mode is preserved by the low decrease in the current I_L in the circuit.

Of course, the present invention is not limited to the circuit example shown in figure 2.

In particular, it applies identically to the electrical circuit of figure 6, which shows a second embodiment of the invention.

In this embodiment, a third diode D_6 and a fourth diode D_3 , respectively analogous to the first diode D_5 and the second diode D_4 , are added to the second branch of the half-bridge, with the result that the third diode D_6 is in series with the other transistor I_1 .

The operation of the resonant generator therefore includes two linear phases, one when the current I_L is positive and the other when the current I_L is negative.

Moreover, as shown in figure 7, it may be beneficial to replace the half-bridge by a complete bridge including four transistors Q_1 , Q_2 , Q_3 , Q_4 .

This circuit can offer particularly high performance if the voltages used are very high, for example of the order of 3000 V, in which case the power delivered by the generator can be as much as 300 kW to 400 kW.

Of course, although there is shown here the supply

of power to a cooking ring F in the form of an inductive load L, R, this type of generator could equally be used to supply a winding of a transformer.

5 Moreover, thanks to the capacitors C_1 , C_2 , the soft switching circuit of the transistors I_1 , I_2 could also be eliminated provided that the semiconductors are able to withstand hard switching.

10 As shown in figure 8, the resonant generator of the invention is particularly well adapted to supply a plurality of cooking rings in parallel.

The generators can therefore be synchronized in frequency whilst operating with different duty cycles (δ_1 , δ_2 , ... δ_n), with the result that the powers transmitted to the cooking rings may be adjusted independently of each other.

15 This type of generator is well adapted to supplying a plurality of cooking rings in the same induction cooking hob, in particular a cooking hob consisting of a large number of inductors in a matrix arrangement in the hob.